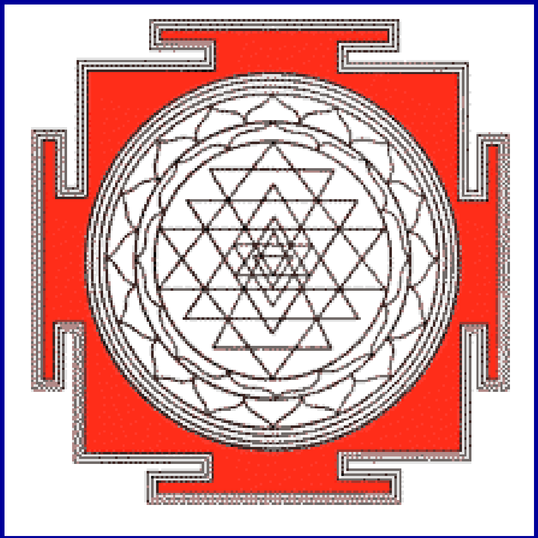
The Anti-Top Quark

The anti-top quark (and its antiparticle) was discovered 10 years ago in collisions of antiprotons and protons. Whereas the antiproton discovery ushered in the Standard Model, the anti-top provided some closure to the story of the microworld of matter.



Top Turns Ten

The antiproton and anti-top share birthday anniversaries.

The top quark tenth anniversary was celebrated at Fermilab last week .

The antiproton was key for the anti-top discovery

Run 1: E_{cm} = 1.8 TeV
$L_{max} = 2\times10^{31}\ cm^{-2}s^{-1}$
Integral = 120 pb^{-1}

Run 2: E_{cm} = 1.96 TeV
$L_{max} = 1.45\times10^{32} cm^{-2}s^{-1}$
>1 fb^{-1} delivered/ expt
maximum $\bar{p}$ stored $=2\times10^{12}$

25 μC of antiprotons have died a horrible death by collision in CDF and DØ

Tevatron physicists and engineers were the real heros

Anti-top to antiproton ratios: Study in contrasts

Charge	2/3
# events in discovery sample	~ 1
Time of our acquaintance	0.2
Mass	190
Number of people required to discover	200
Lifetime (if CPT valid)	$< 10^{-57}$
Integrated world line at Tevatron	$\sim 10^{-12}$
Diameter	$< 10^{-5}$
Freeze out time in early universe	$\sim 10^{-5}$
Electronic channels in discovery experiment	$\sim 10^{4}$

A brief history of the anti-top searches

1977: b-quark discovered at Fermilab

~1990: CLEO & ARGUS show b has $I_W = ½$: need 'top'

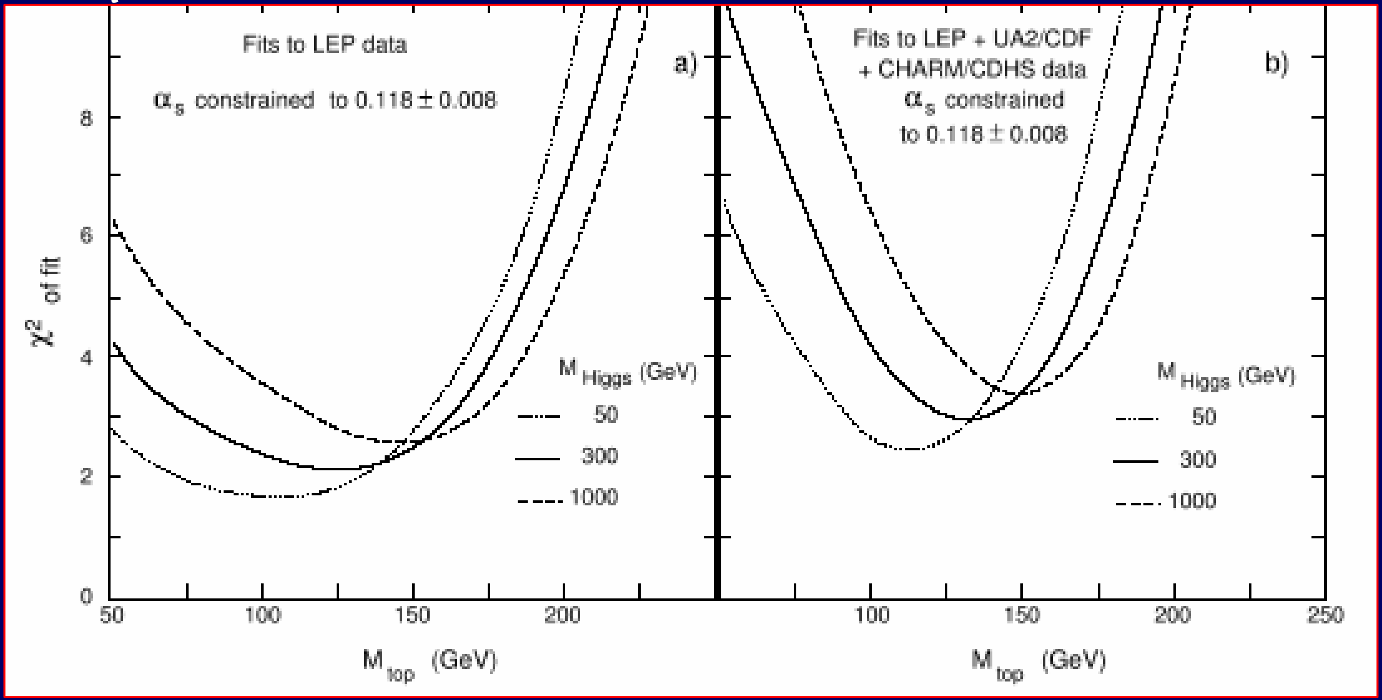
1980 – 1990: Although the 'factor of 3' argument suggested a top quark at ~ 15 GeV, e^+e^- colliders PETRA, TRISTAN, LEP/SLC do not observe top pairs up to M_t = 45 GeV

1984 – 1994: Hadron collider searches raise the limit on M_t: 69 GeV (UA2 and UA1), 91 GeV (CDF), 131 GeV (DØ)

Year	Collider	Particles	References	Limit on m_t
1979-84	PETRA (DESY)	e^+e^-	[45]-[58]	> 23.3 GeV/c^2
1987-90	TRISTAN (KEK)	e^+e^-	[59]-[63]	> 30.2 GeV/c^2
1989-90	SLC (SLAC), LEP (CERN)	e^+e^-	[64]-[67]	> 45.8 GeV/c^2
1984	Sp$\bar{p}$S (CERN)	$p\bar{p}$	[70]	> 45.0 GeV/c^2
1990	Sp$\bar{p}$S (CERN)	$p\bar{p}$	[71, 72]	> 69 GeV/c^2
1991	TEVATRON (FNAL)	$p\bar{p}$	[73]-[75]	> 77 GeV/c^2
1992	TEVATRON (FNAL)	$p\bar{p}$	[76, 77]	> 91 GeV/c^2
1994	TEVATRON (FNAL)	$p\bar{p}$	[79, 80]	> 131 GeV/c^2

A brief history of the anti-top searches

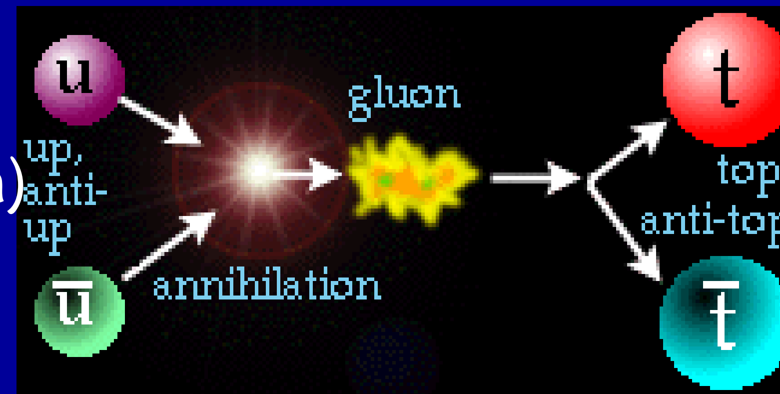
1990- 1994: LEP/SLC precision Z measurements & ν scattering indicate top quark with mass 177 ± 22 GeV, in context of SM. LEP alone predicted somewhat lower.

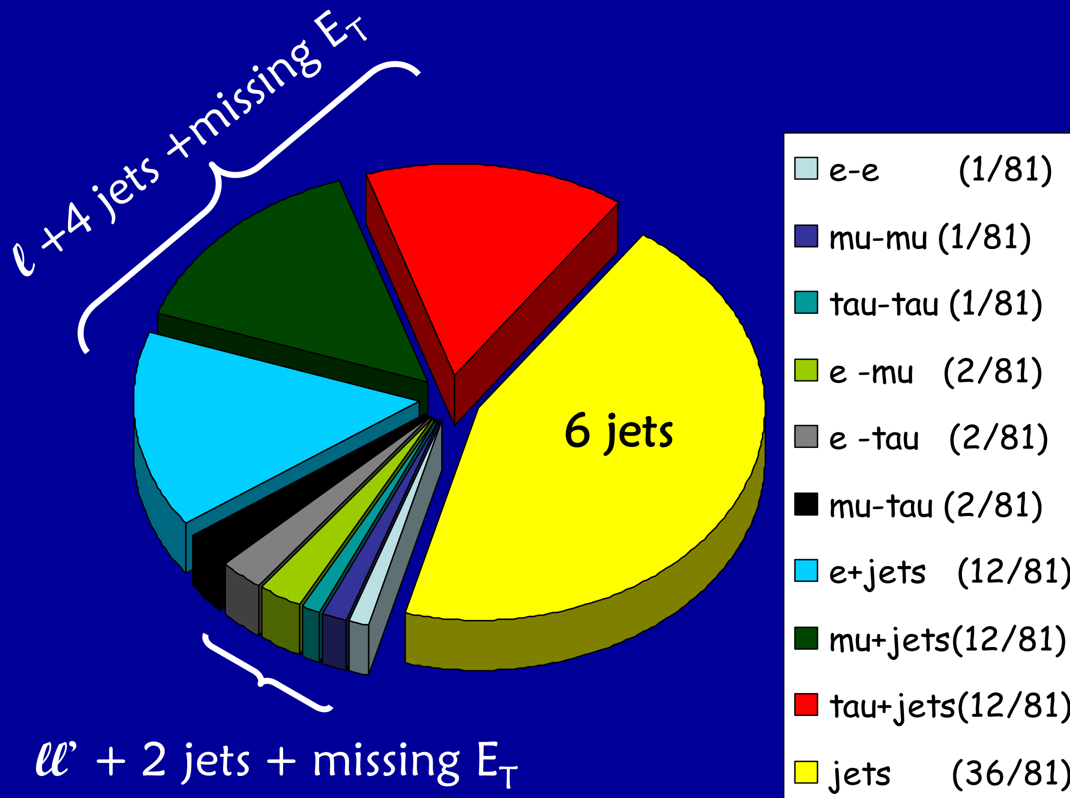


1994: CDF 2.8σ evidence for anti-top with $m_t \sim 175$ GeV, $\sigma_{tt} \sim 14$pb. With same sensitivity, DØ sees only small excess.

Anti-top production and decay

At Tevatron, 85% of $\bar{t}t$ production is from $\bar{q}q$ annihilation (15% gluon fusion)





~100% decays $t \rightarrow Wb$ so final states governed solely by the two W branching fractions (~2/3 qq', 1/3 $\ell\nu$ each). Two of the final jets are b-quarks.

Can have extra jets from initial/final state radiation

The CDF experiment

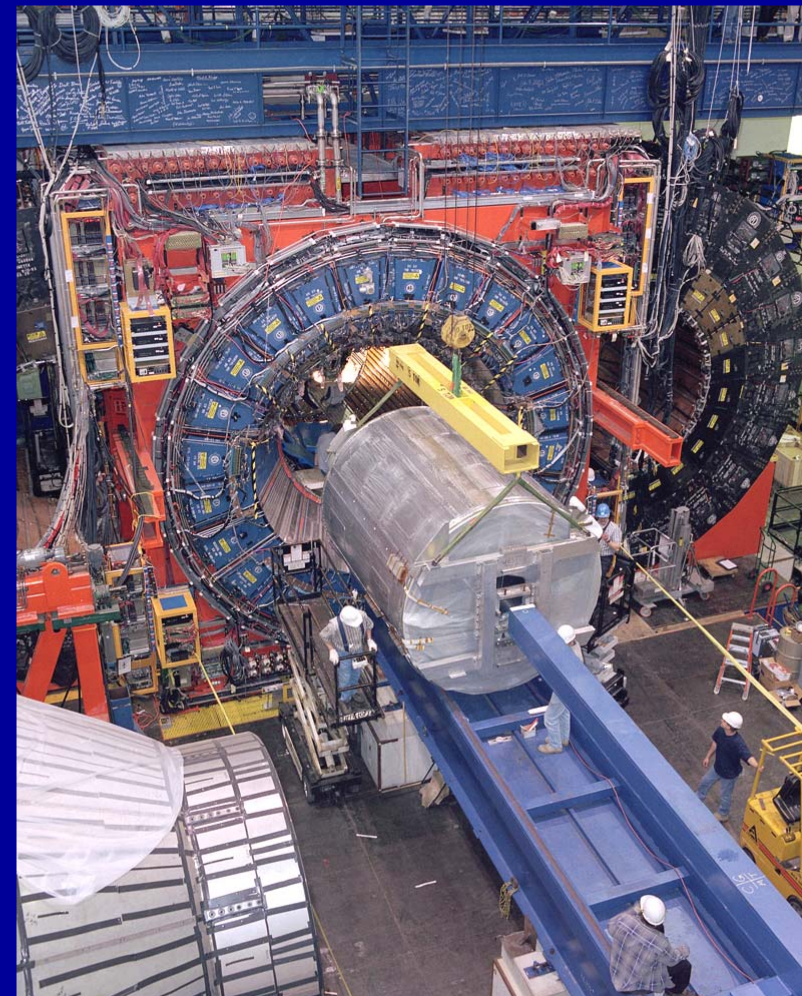
<u>CDF strengths in Run 1</u>

1.5 T solenoid; magnetic tracker,

Silicon microstrip vertex detector (b-quark tagging)

Upgrades for Run 2

Improved calorimetry, new tracker, improved muon detection



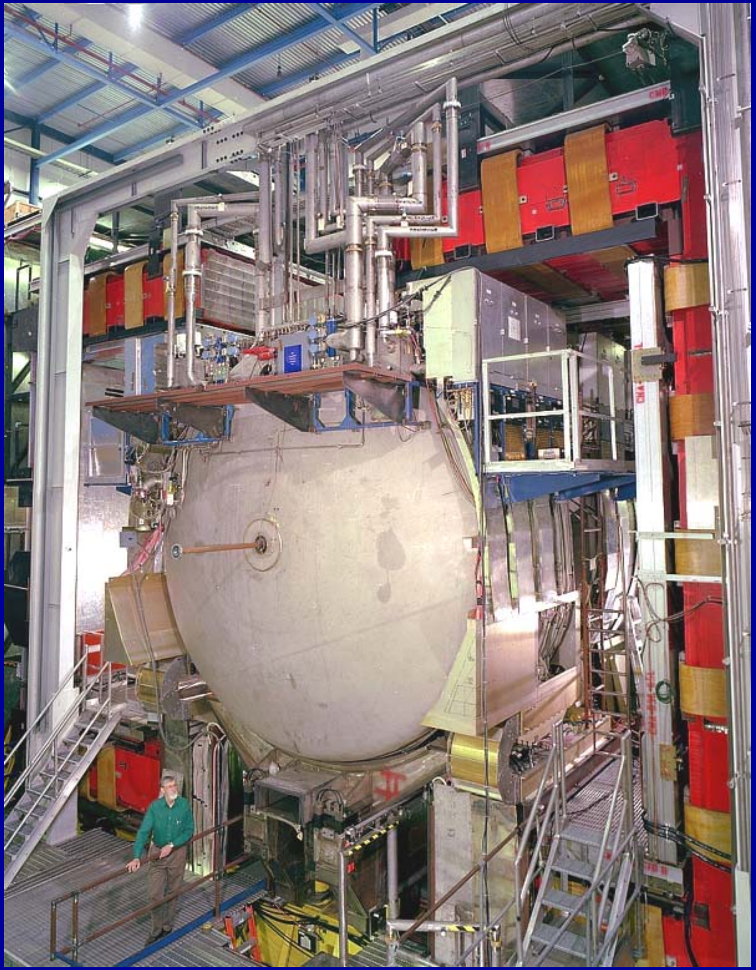
In Run 2, CDF evolved to look more like DØ

The DØ experiment

DØ strengths in Run 1

Hermetic, fine segmentation U-LAr calorimetry (e, jets, missing E_T)

Full coverage muon detector



Upgrades for Run 2

Added 2 T solenoid, magnetic tracking, silicon vertex detector

In Run 2, DØ evolved to look more like CDF

The anti-top discovery – 1995

Both CDF and DØ selected **dilepton** (e or μ) + jets events and **single lepton** (e or μ) + missing E_T + 3 or 4 jets. (Analyses using the all-jets samples followed later.)

The **dilepton analyses** were similar: cuts placed on E_T of leptons, jets and missing transverse energy.

CDF found 6 events, with background estimate of 1.3 ± 0.3 events.

DØ found 3 events, with background estimate of 0.65 ± 0.14 events.

The anti-top discovery

For **single lepton** analyses, both experiments required **e** or μ, missing E_T, and at least 3 jets.

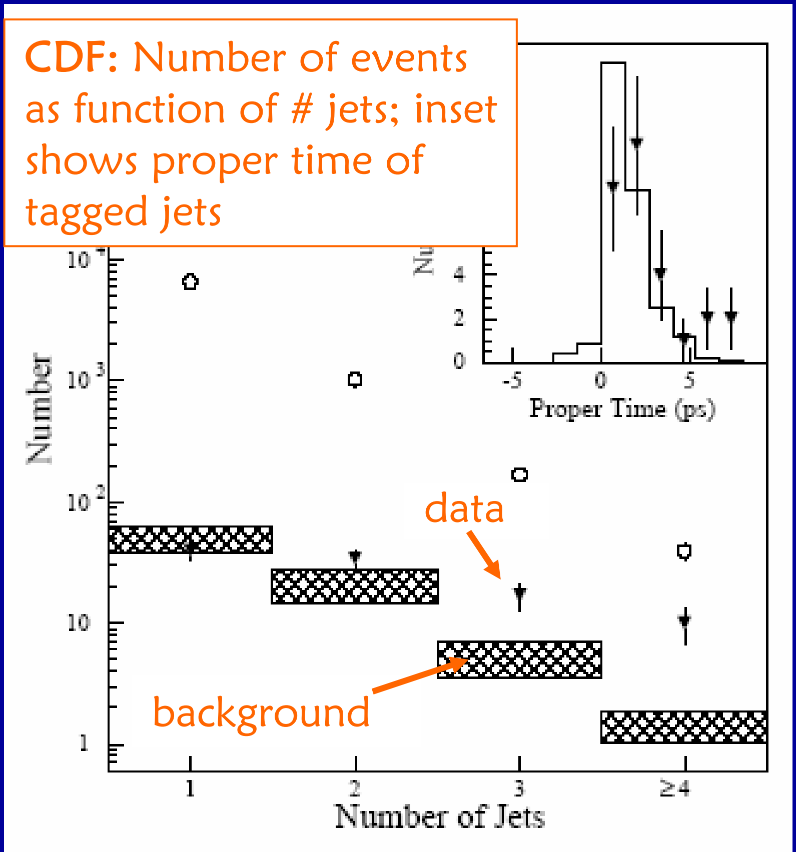
CDF required at least one jet tagged as b with a displaced vertex using the silicon vertex detector, or soft leptons from $b \rightarrow \ell X$.

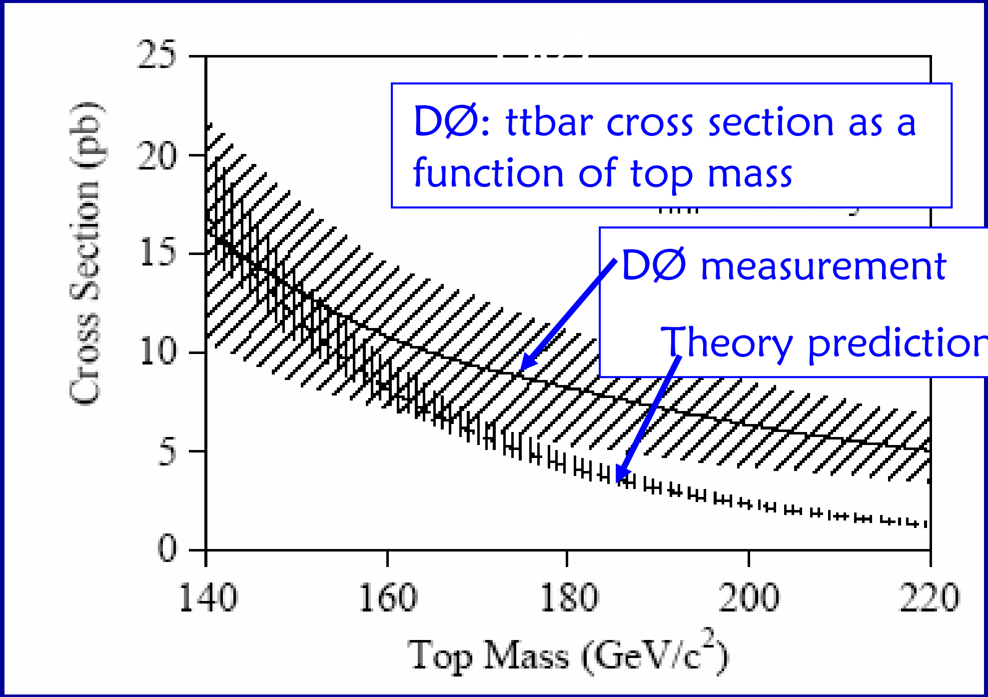
CDF found 37 events with 50 b-tags; number of background tags estimated at 22.1 ± 2.9

In the DØ analysis, untagged events were required to have at least 4 jets, and topological cuts made on aplanarity (top decays are isotropic) and $H_T = \Sigma_{objects} | p_T |$ (to enhance large mass $\bar{t}\, t$ production). Events with a soft muon tag were accepted with 3 or more jets.

DØ found 14 events; background estimated at 3.1 ± 0.5 evnts

The anti-top discovery



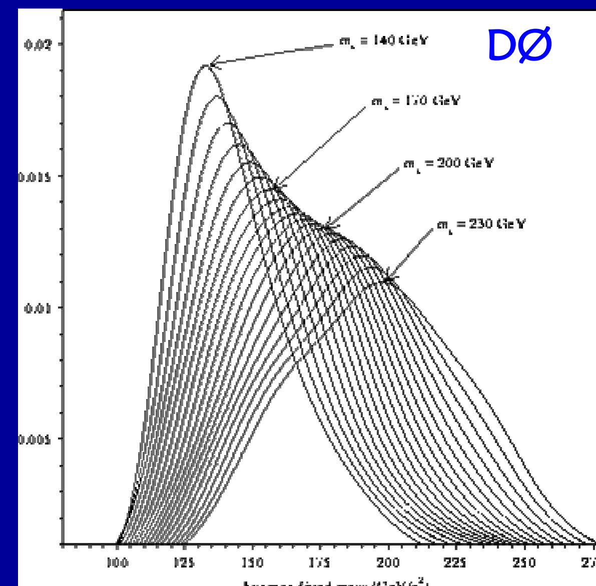


Estimated significance of signal excess:
CDF: 4.8σ. DØ: 4.6σ

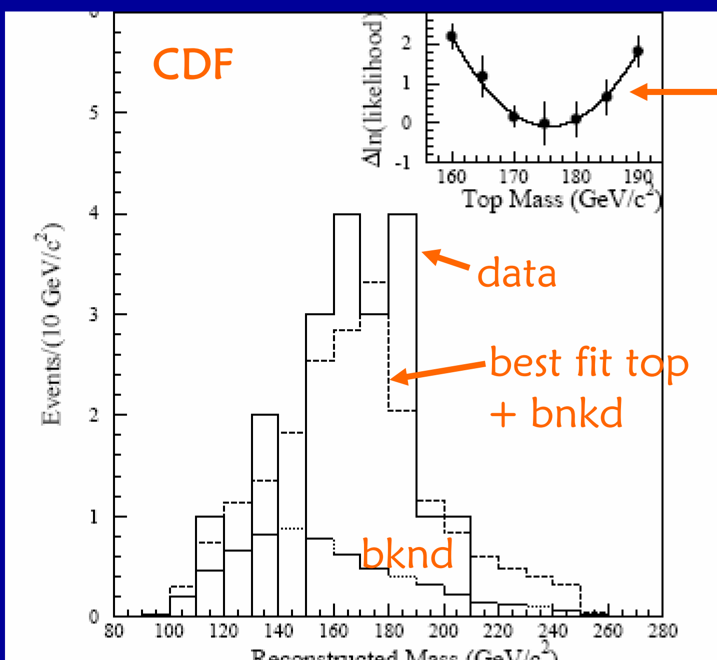
The mass determination

Kinematic fit of lepton+4 jets events (with missing ν, 2C fit).

Make templates of 'fitted' mass for a set of true top mass hypotheses, plus expected background.



fitted mass



fitted mass

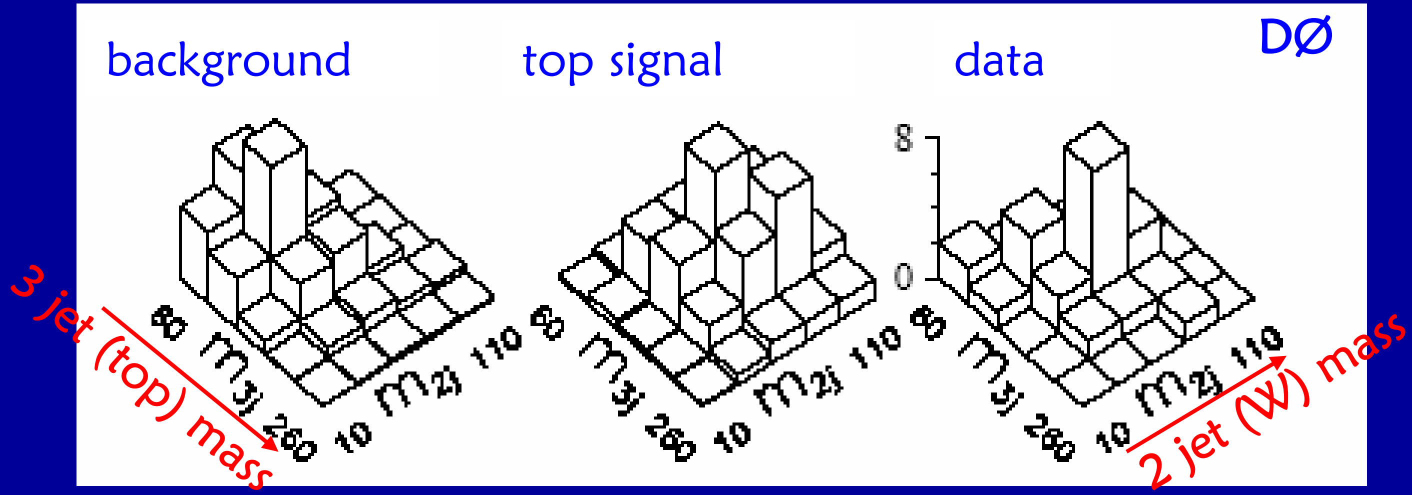
χ^2 vs. true top mass

Find the mass template giving the best χ^2 fit

The mass determination

Cross checks: Analysis with looser cuts gave consistent results.

Look for evidence of W → qq (dijet mass) in top signal sample.

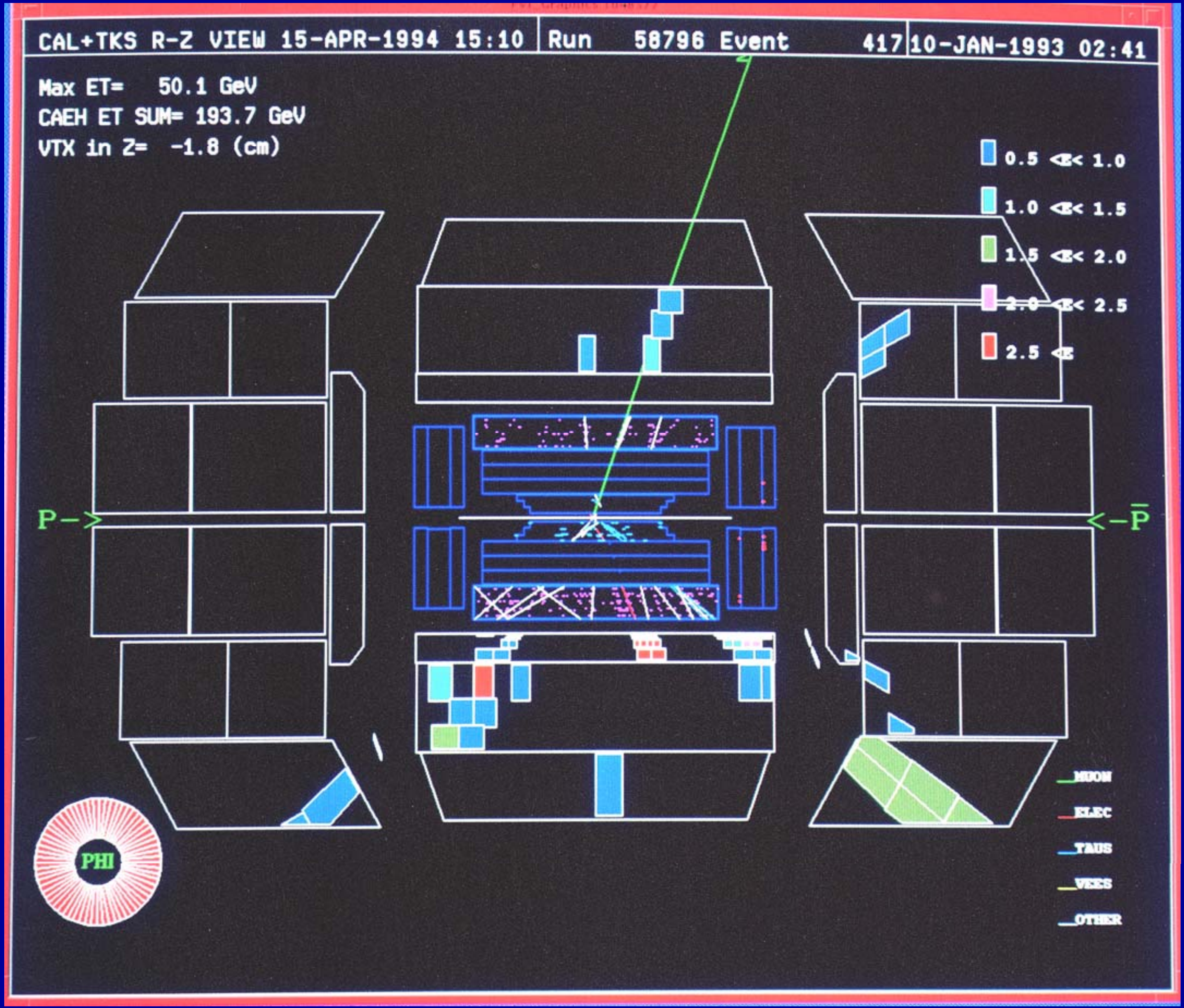


Mass result:

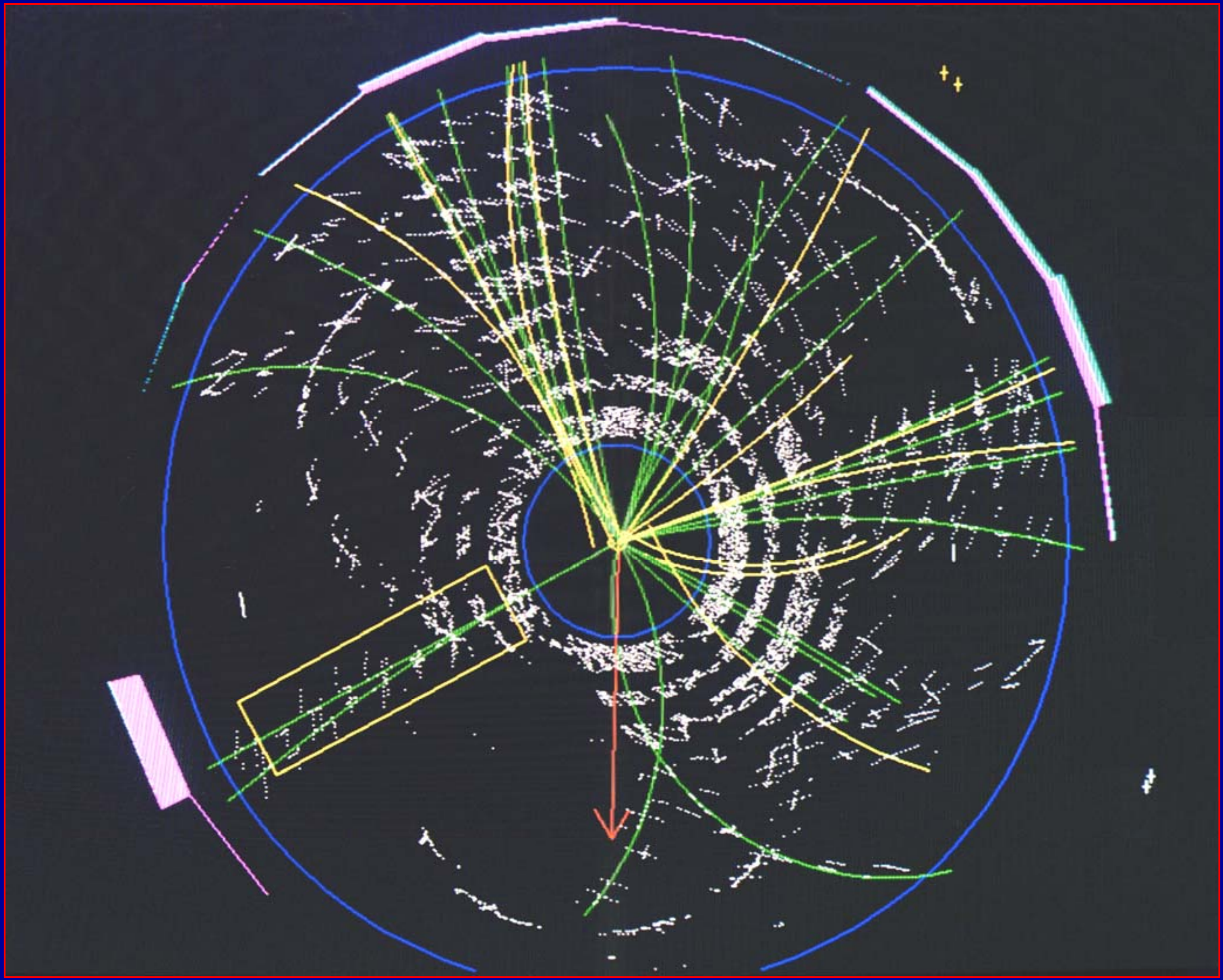
CDF: $M_t = 176 \pm 13$ GeV

DØ: $M_t = 199 \pm 30$ GeV

A DØ event: e, μ, 2.5 jets + missing E_T



A CDF event: e, 4 jets + missing E_T



A collaborative venture

For the CDF and DØ anti-top discoveries:

Crucial contributions from virtually all authors – detectors, software, operations, analysis, leaders etc.

Large collaborations of N people have great power when coherent. Effectiveness ~ N^m $(0 < m < 1)$.
In the case of the anti-top discovery, m became close to 1.

These large experiments are really done with dozens of small clans of 3-4 people (like the pbar discovery experiment); banded into villages (top to μ+jets etc.); provinces (top group); united into the Confederacy of CDF or Duchy of DØ

The intellectual power resides in the small clans of 3-4 people.

Digging out the signal

The fraction of $t\bar{t}$ events in $\bar{p}p$ collisions is $1\text{x}10^{-10}$. One must design the detectors well, and be clever in selecting events and analyzing them.

Devising the triggers is a key issue for hadron collider experiments: One can log only 10^{-5} of collisions.

Need high reconstruction efficiency for e, μ, jets and missing E_T. Efficient b-tagging allows access to $t\bar{t} \rightarrow 6$ jets.

Top mass measurements needed special selection variables, chosen to have little dependence on the actual mass.

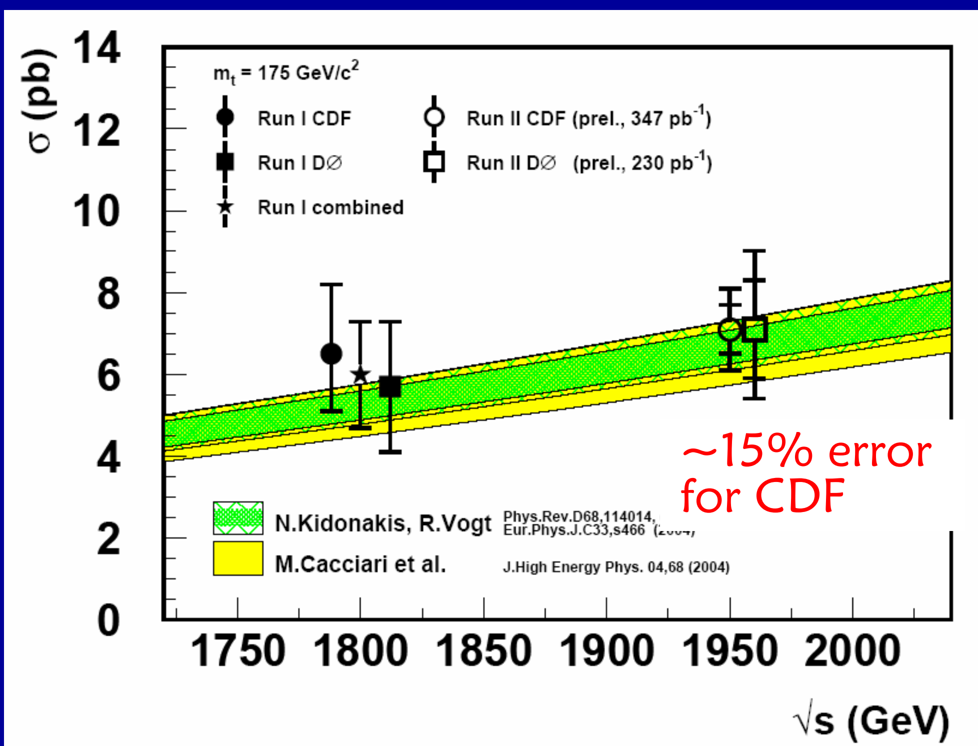
Neural networks allow complex cut contours, so some quantities not very top-like can be balanced against those that are.

Use of production and decay matrix elements as weights can significantly improve precision.

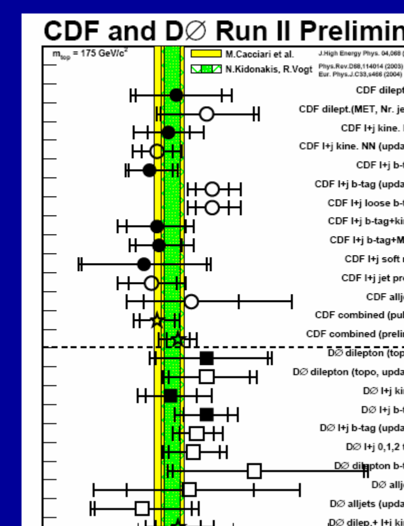
What do we know today ?

CDF and DØ in Run II, over 1 fb^{-1} now delivered to both detectors; analyses on about 1/3 to 1/2 of this sample.

$\bar{t}\,t$ cross section



Good agreement with the resummed NNLO QCD prediction. Dilepton, single lepton and all jets channel measurements agree.

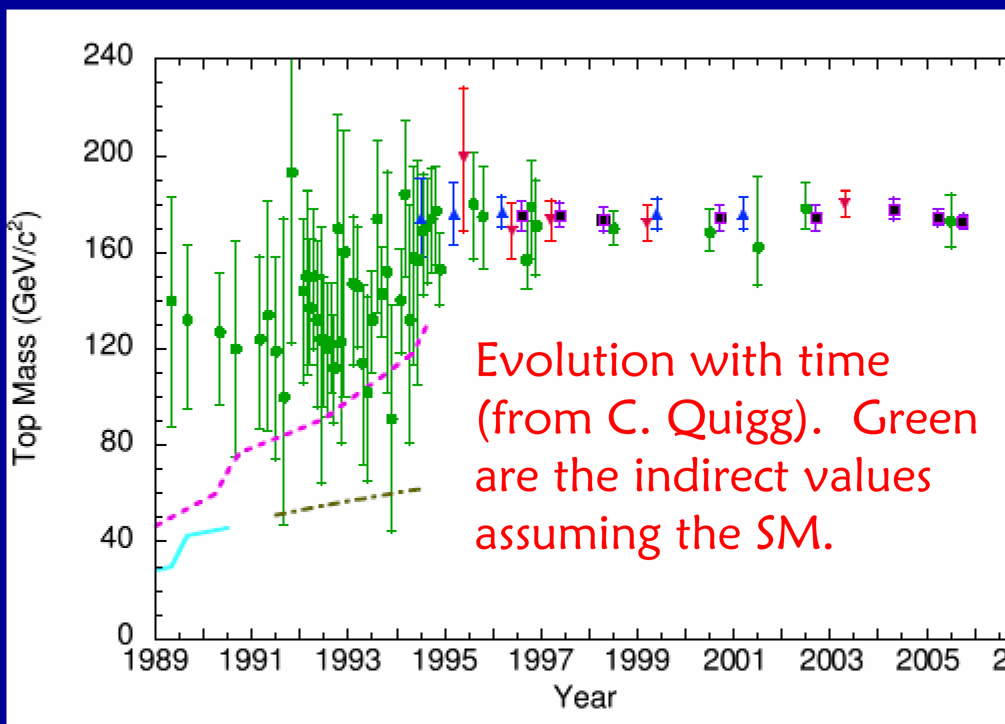


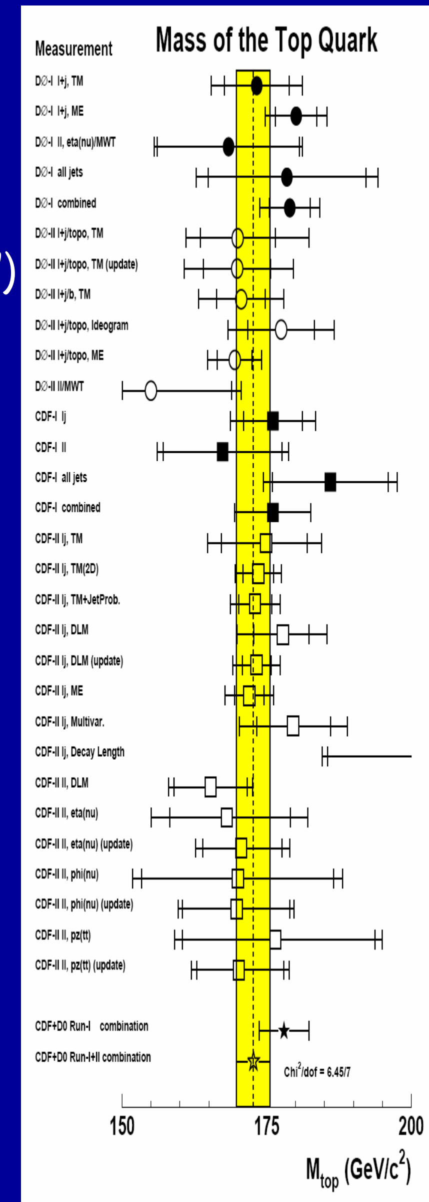
Updated mass measurement

anti-top quark mass

Combination of all CDF and DØ measurements:

$M_t = 172.7 \pm 2.9$ GeV (ultimate Tevatron error ~1.4 GeV)

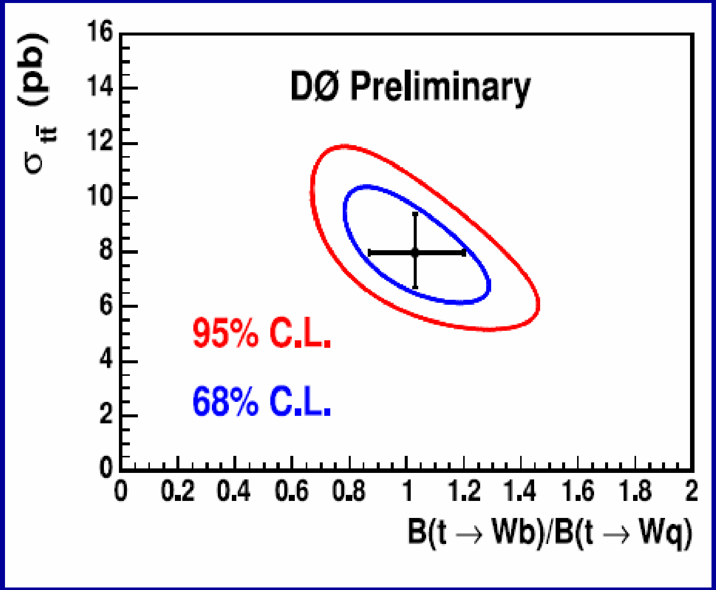




Top is the most accurately known quark mass (1.7%)

Decays of anti-top

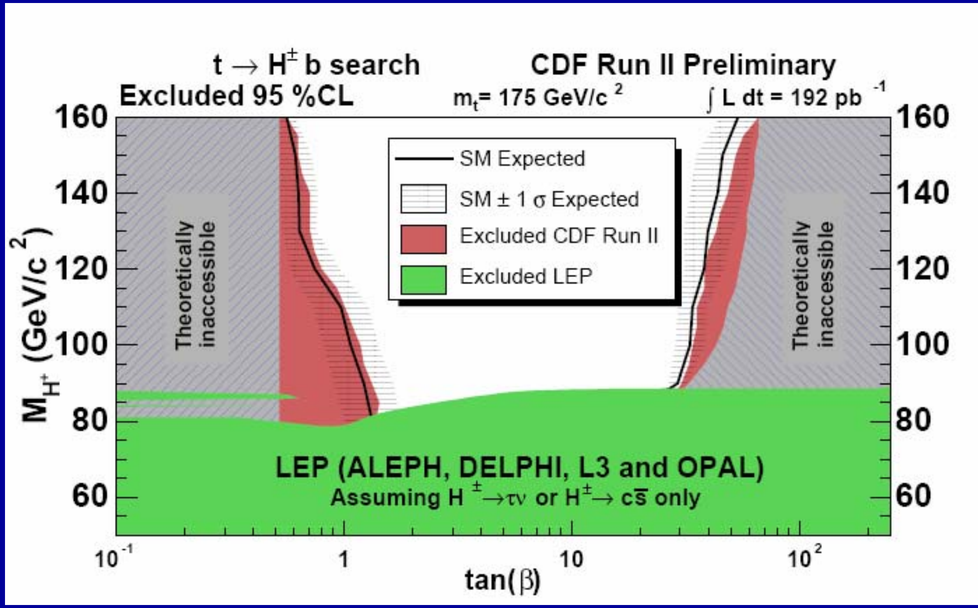
Branching ratio to Wb



BR(t→Wb) / BR(t→W q) $=1.03^{+0.19}_{-0.17}$
(simultaneous fit with σ_{tt})

Decay to H⁺b ?

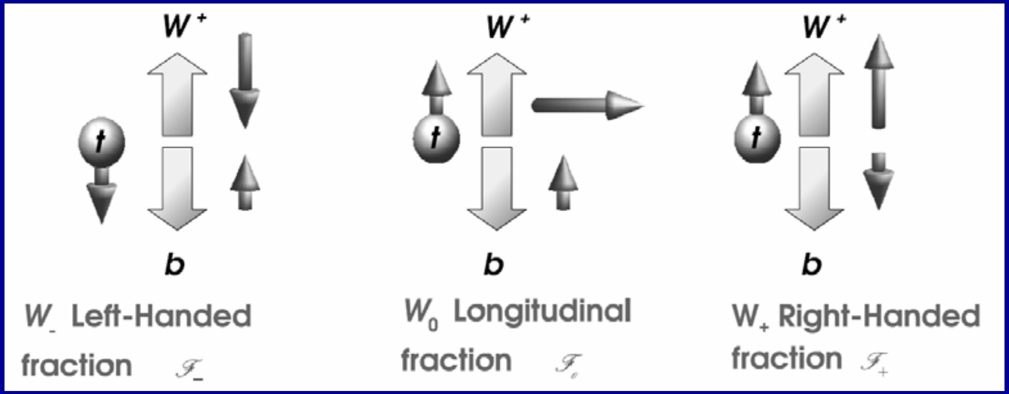
If top decays to the SUSY H^+, expect enrichment of τν or cs final states. Extend H^+ mass exclusion for low and high tanβ)



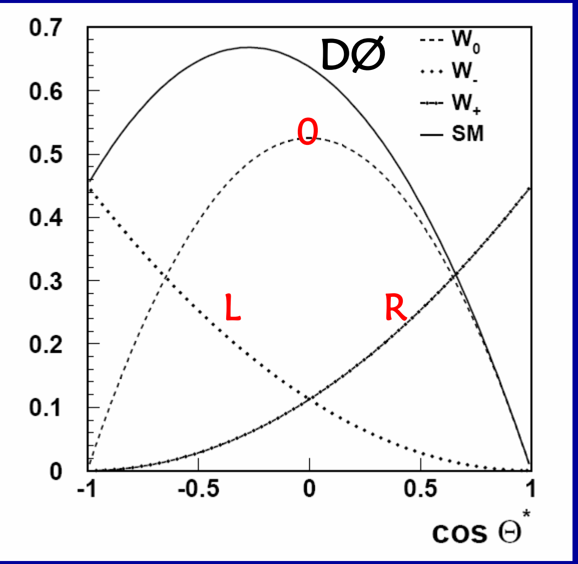
Couplings

V-A coupling?

SM says that the W helicity in top decay is 70% longitudinal polarization and 30% left-handed (no right-handed W).



Assuming F_0 = 70%, F_+ < 0.25 (95% CL)



Angle of ℓ vs. top direction

Flavor Changing Neutral Current decays

(CDF): $B(t\rightarrow c\gamma) + B(t\rightarrow u\gamma)$ < 3.2% (95% CL)

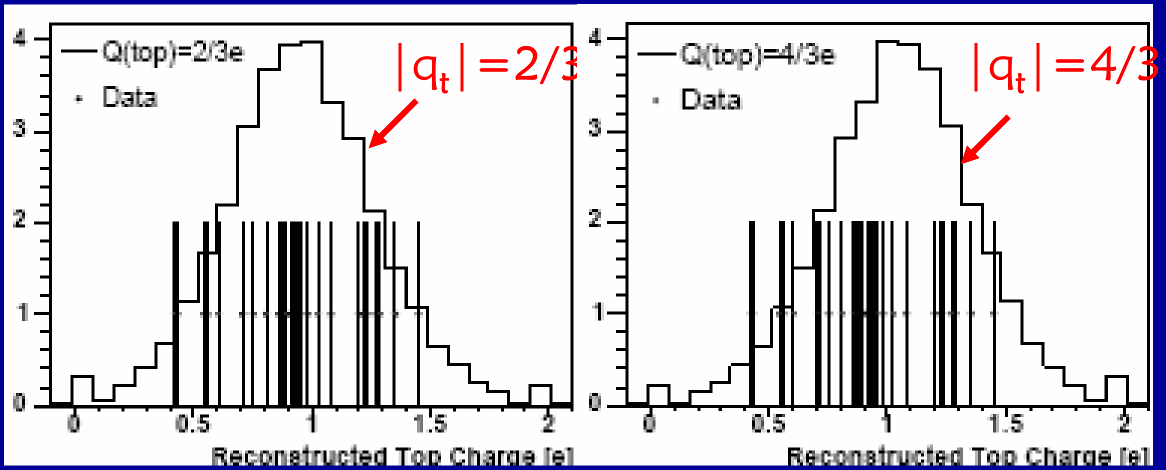
$B(t\rightarrow cZ) + B(t\rightarrow uZ)$ < 33% (95% CL)

Intrinsic properties

Top quark charge

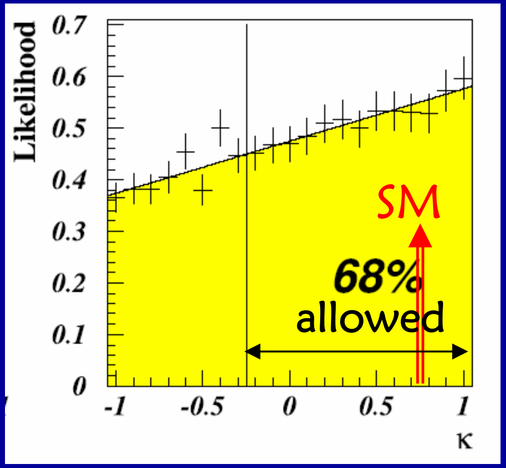
'Top' could be decaying into W^+b or W^-b, so could have charge +2/3 or –4/3.

DØ measures b and W charge to find $|q_t|=2/3$ favored at 93.7% level.

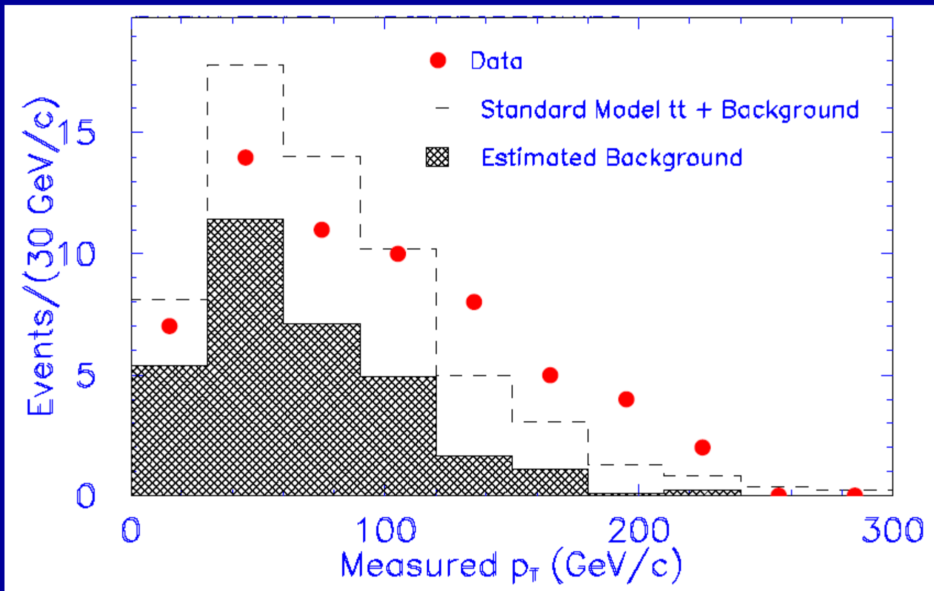


Spin correlations

Anti-top and top decay before fragmenting, so spin alignment is preserved in decay. The SM predicts large spin correlation. The lepton momenta in dilepton events are correlated with top spin.

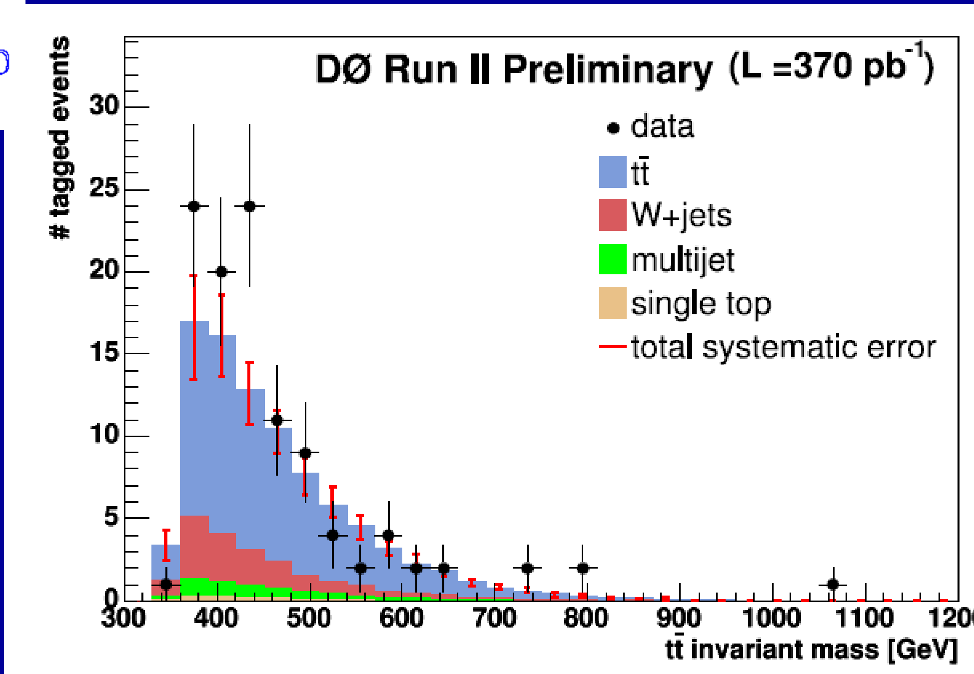


Production of $\bar{t}t$ pairs

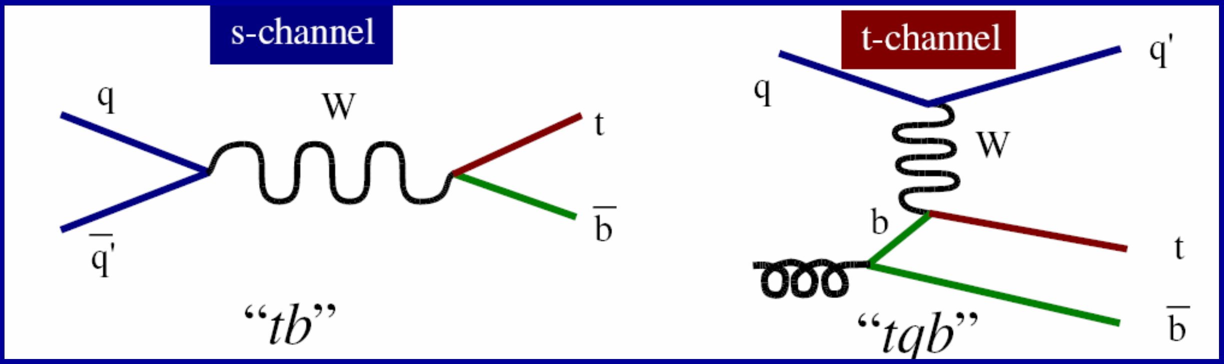


CDF: reasonable agreement of anti-top p_T distribution with SM QCD prediction.

DØ: reasonable agreement of measured $\bar{t}t$ mass distribution with QCD prediction.



Electroweak production of single anti-top



σ_{SM} = 0.9 pb σ_{SM} = 2.0 pb

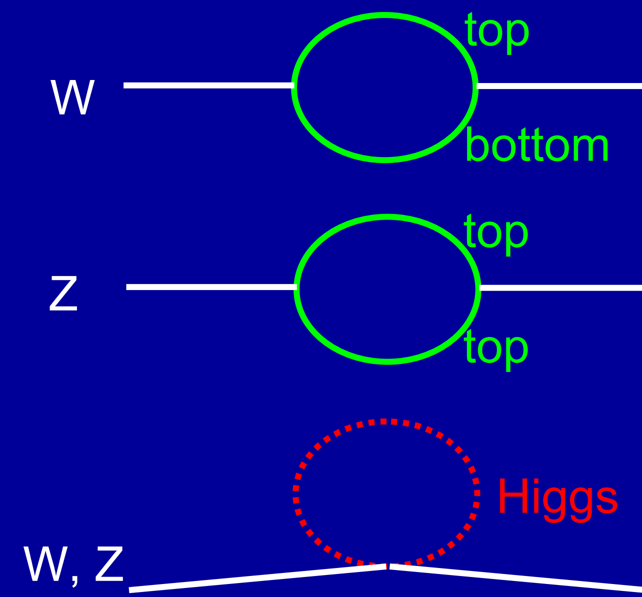
Single top XS allows determination of $|V_{tb}|$

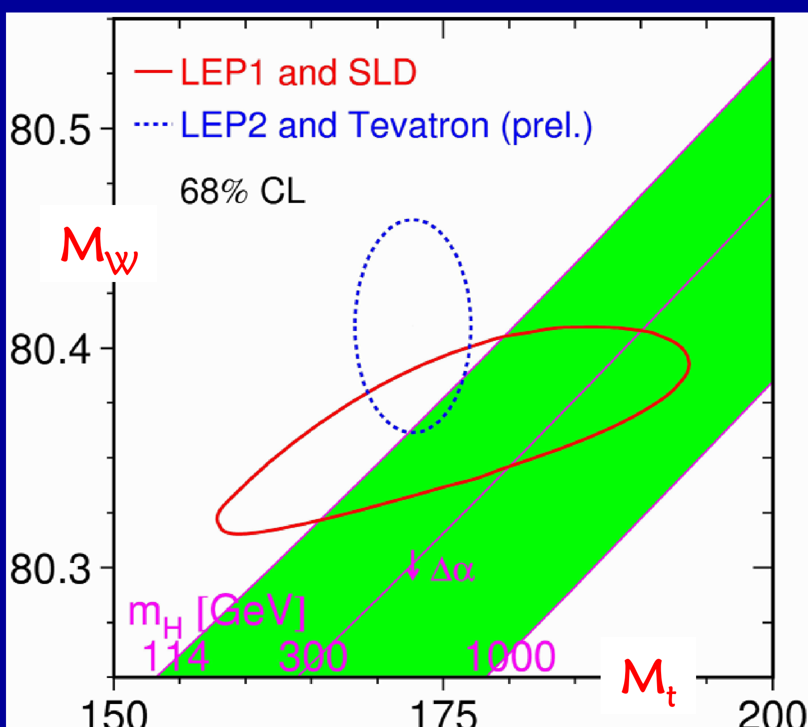
Limits			
s-channel	t-channel		
12.1 pb	11.2 pb	CDF	(162 pb^{-1})
5.0 pb	4.4 pb	DØ	(370 pb^{-1})

Expect to see electroweak single top with > 2 fb^{-1}

Precision Electroweak tests with top

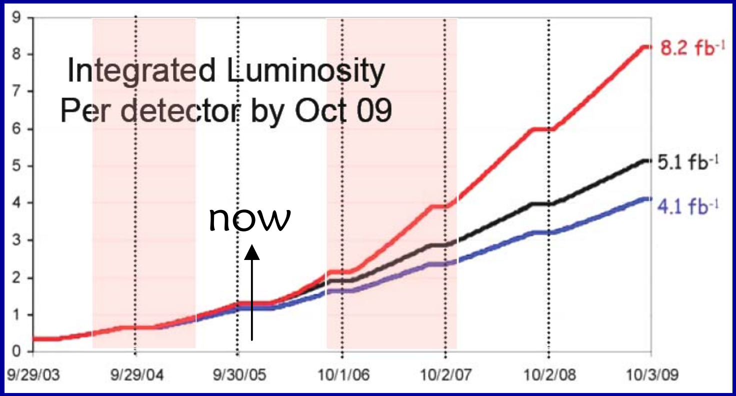
Top and Higgs loop corrections modify the W and Z masses; precision measurement of W, Z, t masses allow inference (within SM) of Higgs mass.





Current top and W mass measurements, with LEP/SLC Z data, predict Higgs mass below 200 GeV in SM. The data are pushing toward the region where SUSY Higgs is preferred.

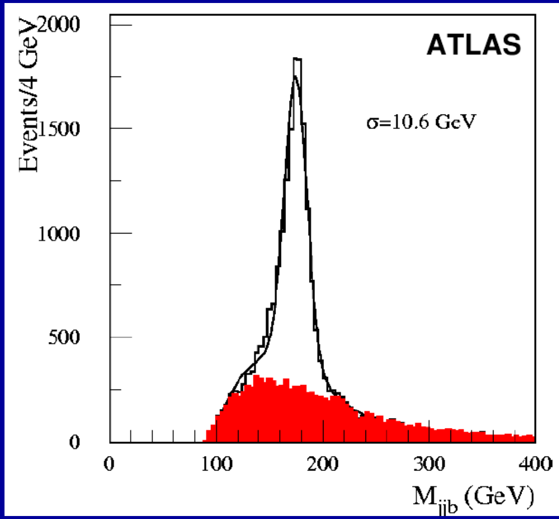
Future for anti-top studies

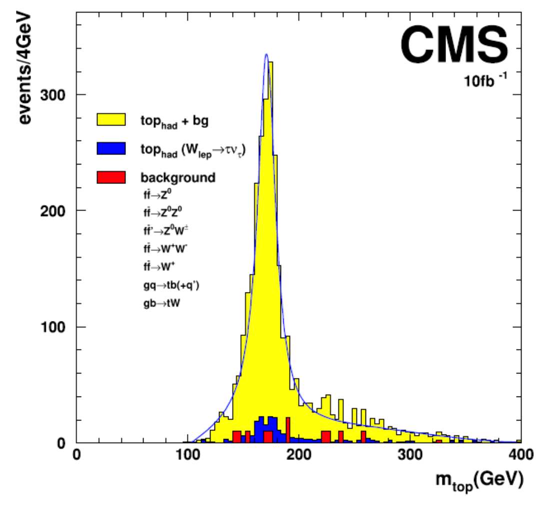


Tevatron: expect 8x luminosity by FY09 – many top studies are statistically limited.

LHC produces 1 $t\bar{t}$ event/sec at $L=10^{33}$; higher p_T than Tevatron (more collimated), more forward, more background, but with good selection criteria will have very clean samples.

Lepton+jet fitted mass distributions in 10 fb^{-1}; statistical error ~0.1 GeV; systematic error ~ 1 GeV





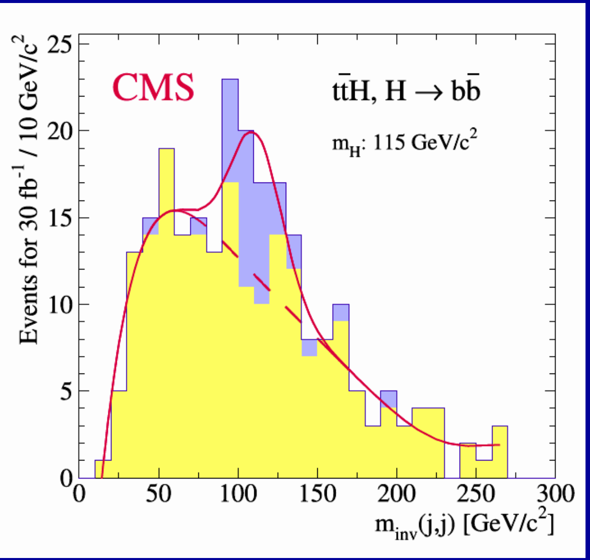
Future for LHC anti-top studies

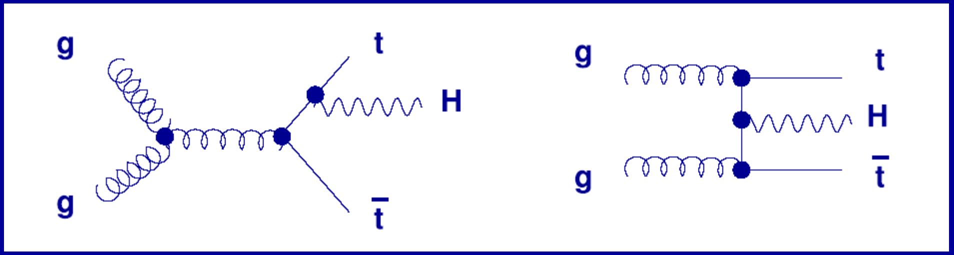
At LHC, expect W helicity fractions: $\delta F_0 \sim 2\%$ (F_0=70% in SM) and $\delta F_+ \sim 1\%$ ($F_+ = 0$ in SM)

Sensitivity to rare decays range 10^{-3} (Zq) – 10^{-7} (WbZ)

Single top cross section to 10% giving $|V_{tb}|$ to 5%

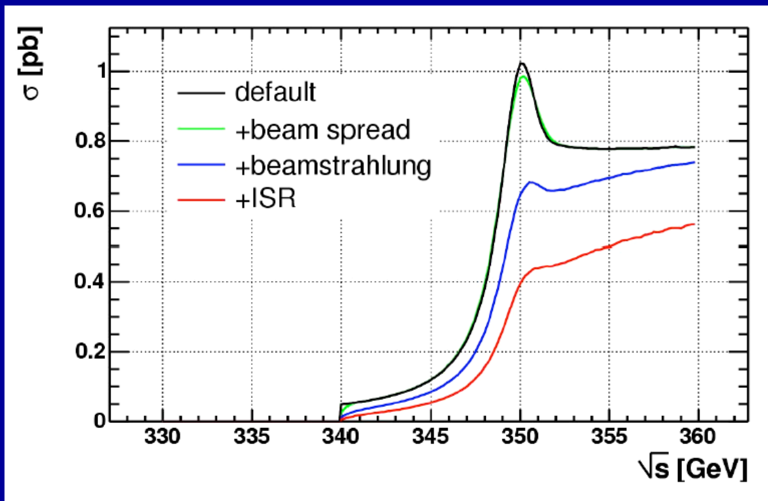
Yukawa coupling (ttH)





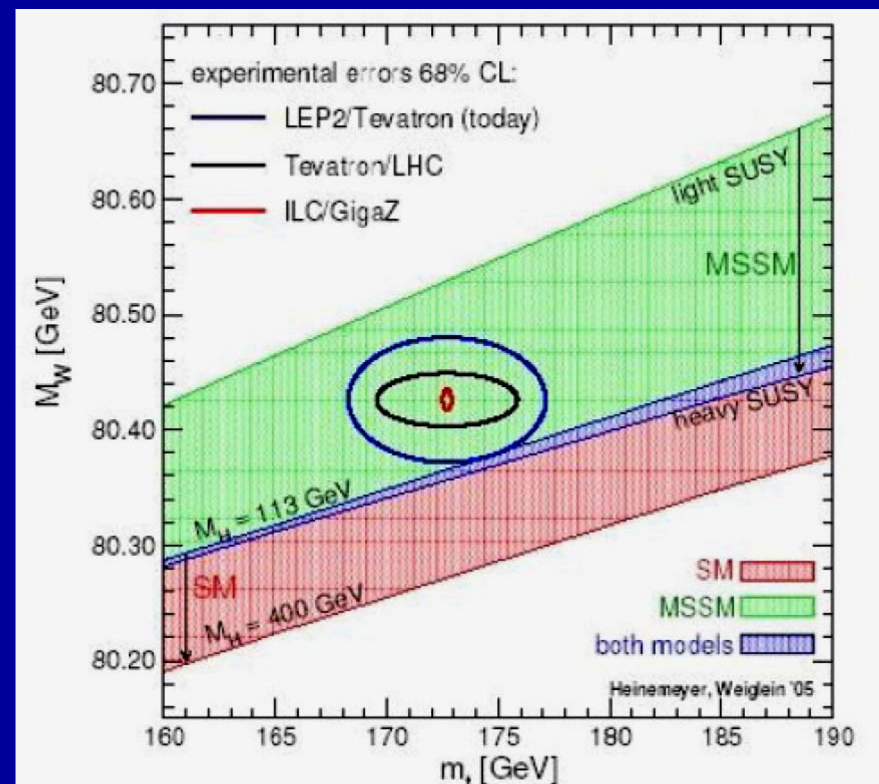
Expect 12% precision on top Yukawa coupling with 100 fb^{-1} at LHC (and ILC for BRs).

Anti-top at the ILC



Threshold curve for $\bar{t}t$ production contains information on M_t, G_t and α_S. Threshold scan would give $\delta M_t \sim 40$ MeV, $\delta\Gamma_t \sim 50$ MeV (with improved QCD calculation).

ILC accuracy on M_t, M_W, and M_{Higgs} gives very tight constraint on the model consistency – and a view to physics beyond the SM.



Legacy of the antiproton

As so often happens, yesterday's discovery is today's tool. The antiproton can be directed oppositely to protons in the same magnetic channel ⟹ SppS and Tevatron.

The antiproton colliders have crucially influenced our view of the particle world – bringing the discovery of the W and Z bosons, uncovering parton jets as observable signatures of quarks and gluons, observing heavy b-quark states, and discovering anti-top and its antiparticle.

We may still hope for further advances – B_s mixing, discovery of the Higgs boson, supersymmetry or ?? – before the return to proton-proton collisions with the LHC.

Legacy of the anti-top

The existence of the anti-top was not a great surprise. So far it conforms well to SM expectations. But measuring its properties accurately offers powerful insights into the physics of the TeV scale.

The anti-top is the only quark that we are able to observe in its naked state, so has a special status.

The large anti-top mass – at the EW symmetry breaking scale – seems bizarre. But it may well turn out that the top mass is normal and the small (u,d,c,s,b) masses are the anomalies. Top may play a special role in EW symmetry breaking and in the decays of particles associated with new symmetries.

The Anti-Top Mandala

The connectedness
of things

A gateway to
understanding

The eightfold way
to unification

The structure of
the universe